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End-to-end communications in low-rate wireless networks: Problems and solutions in satellite scenarios

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Resumen

Desde que el Sputnik 1 fue lanzado por primera vez en 1957, los satélites han tomado el mundo con sus múltiples aplicaciones en nuestro, especialmente en el campo de las telecomunicaciones, desde la emisión de televisión a las comunicaciones móviles. Uno de los principales problemas que presentan, es que un solo satélite no puede proporcionar una comunicación de extremo a extremo entre dos puntos muy distantes entre sí. Este problema implica que una red contínua entre estos dos puntos no se puede implementar, y es por eso por lo que muchas empresas públicas y privadas han estado trabajando durante mucho tiempo en grupos de satélites para proporcionar una cobertura global de la Tierra.

En la última década, las comunicaciones M2M (machine-to-machine) se han convertido en uno de los campos más avanzados en el mundo de la ingeniería, y lo están cambiando con el fin de crear un futuro más sofisticado y automatizado. Este tipo de comunicaciones sin hilos de bajo ritmo de bit puede ser apoyado en una red de satélites, pero que a veces requiere una baja latencia en su canal.

En este proyecto, varios escenarios de redes de satélite son simulados con el fin de estudiar los diferentes retardos en todos ellos y encontrar la manera de optimizar la latencia en la comunicación M2M entre dos puntos fijos en el mundo, usando la creación de una red continua hecha de satélites GEO y LEO. El proyecto se centra en la idea de encontrar la mejor arquitectura de satélites para obtener una comunicación fluida y sin ningún retraso relevante en el camino, así como en discutir el equilibrio entre el retardo de la señal y el consumo de energía del satélite, especialmente en el caso de nanosatélites.

Resum

Des de que l'Sputnik 1 es llançava per primer cop el 1957, els satèl·lits han dominat el món amb les seves múltiples aplicacions en la nostra vida quotidiana, especialment en el camp de les telecomunicacions, des de difusió de televisió a les comunicacions mòbils. Una de les principals qüestions que presenten, és que un únic satèl·lit no pot proporcionar una comunicació extrem a extrem entre dos punts molt distants. Això implica que mai no es pugui implementar una xarxa contínua entre aquests dos punts, i és per això que moltes empreses públiques i privades han estat treballant durant molt temps en agrupacions de satèl·lits per donar cobertura global de la terra.

En la darrera dècada, les comunicacions de M2M (machine-to-machine) han esdevingut un dels camps més avançats del món de l'enginyeria, ja que estan canviant-lo per tal de crear un més sofisticat i automatitzat futur. Aquests tipus de comunicacions sense fils de baix ritme de bit poden ser recolzades en una xarxa de satèl·lits però de vegades requereixen una latència baixa al seu canal.

En aquest projecte, diversos escenaris de xarxes de satèl·lits són simulats per tal d'estudiar els diferents retards en tots ells i en trobar la manera d'optimitzar la latència en la comunicació M2M entre dos punts fixos en el món, utilitzant la creació d'una xarxa contínua de satèl·lits GEO i LEO. El projecte es centra en la idea de trobar la millor arquitectura de satèl·lits per obtenir una comunicació fluida sense demora pertinent en el camí, així com en discutir la solució de compromís que existeix entre el retard del senyal i el consum energètic del satèl·lit, especialment en el cas dels nanosatèl·lits.

Abstract

Since the Sputnik 1 was first launched in 1957, satellites have taken over the world with their multiple applications in our day-to-day life, specially in the telecommunications field, from television broadcast to mobile communications. One of the main issues they present, is that a single satellite can't provide an end-to-end communication between two spots widely separated. This issue implies that a continuous network between these two spots can never be implemented, and that's why so many public and private companies have been working for a long time in clusters of satellites to provide global coverage of the earth.

In the last decade, the M2M (machine-to-machine) communications have become one of the most advanced fields in the engineering world, as they are changing it in order to create a more sophisticated and automatized future. These type of low-rate wireless communications can be supported in a satellite network but they sometimes require a low latency in its channel.

In this project, several satellite network scenarios are simulated in order to study the different delays in them and to find the way to optimize the latency in the M2M communication between two fixed spots in the globe, while creating a continuous network made out of GEO and LEO satellites. The project is focused on the idea of finding the best satellite architecture to obtain a fluid communication without any relevant delay along the way, as well as discussing the trade-off between the delay of the signal and the energy consumption of the satellite, specially in the nanosatellite case.

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Chapter 1

Introduction

1.1 Project Statement

In the growing era of the Internet of Things (IoT), in which the main concept is to create an interconnected device network capable of interacting and exchanging data between them, the machine-to-machine communications are the key to it. The M2M network has a lot of possible applications such as security enhancement, tracking, healthcare and -most importantly- remote monitoring and control. This last use of M2M is more commonly known as telemetry, a communication process by which measurements are made from different remote or inaccessible points in order to be monitored in another location. These measurements might be anything that can be easily quantified by sensors or other small devices, from temperature and humidity values to telemedicine. All telemetry communication processes may be wireless or wired, and they usually imply a low data transmission from a sensor or another adequate device where the information is stored and divided in small packets and sent in a certain amount of time to the main monitoring station.

Satellite networks are very useful for creating a connection between two very distant spots where one of them (or both) are in a remote or inaccessible area and with no terrestrial connection. Therefore, it could be the case that a wireless telemetry link between two spots could not be done without satellite connectivity. These links always encounter themselves in the L band (1-2 Ghz)[1], the same band used for other applications such as mobile communications.

However, the type of satellite is a very important matter in this issue, as it exists a huge difference in a case where regular-sized satellites are used than in a case where a nanosatellite is used, such as the CubeSat[1]. The satellite parameters from one case to the other can vary a lot, resulting in a totally different scenario where some parts of the link gain a lot of importance, specially the energy consumption and harvesting. As the nanosatellites are unable to have the power that a normal-sized satellite does, the link becomes more critical and that is where relation between the delay and the energy consumption of a satellite appears.

This project has used these three previous paragraphs as context for the study of the delay of a telemetry packet between two very distant spots. The first end is a remote or inaccessible area where certain telemetry data is wanted and the other is the monitoring station where the telemetry data is going to be studied in.

[1] http://www.cubesat.org/

Throughout the next chapters of this Thesis, the definition of multiple scenarios including Low-Earth Orbit Satellites and Geosynchronous satellite will be made in order to study the delay of the signal depending on the parameters of the link between the ground station and a satellite and the inter-satellite links (ISL) required for the transmission. The aim is to compare the different delay times that the different satellite constellations imply to this end-to-end transmission, while showing results in different figures and tables of those particular delays in relation with the energy consumption of the satellites or the number of inter-satellite links used.

This project seeks to give a global sight of all the crucial parts that involve a M2M communication link such as the proposed one, as well as finding the optimal path of the signal depending on two major variables already explained, time and energy.

1.2 State of the Art

There are many recent studies and papers regarding the delay in a LEO satellite constellation [2], as well as proposed routing algorithms mainly focused on the search for the minimum time in the transmission. Some of these studies present new advanced theoretical ways to reduce the delay by creating a tree of probabilities based on all the different paths that the signal can go through from the user transmitted to the user receiver[3]. These paths are usually analyzed with a probability density function in order to see which are the most probable paths the signal is going to take.

However, the delay in the signal not only depends on these routing algorithms. The inter-satellite links are a main issue in these type of scenarios, as a bad link between two satellites could cause a major increase in the delay of the signal, specially in LEO satellites[4]. Regarding the GEO satellites constellations, more recent studies have been released in order to optimize the link budget in the GEO inter-satellite link, increasing some parameters of the transmission to balance the damaging effect of the long distance -and therefore, considerable attenuation- between two GEO satellites[5].

The search for the optimal delay in a satellite constellation is a general issue, and therefore an analysis has to be done in order to provide the lower latency in the link that has been introduced in the previous chapter, which involves telemetry or machine-to-machine technologies (Internet of Things -IoT). Many research has already been done in the past few years in this matter, not only focused on the low propagation delay, but also in the enhancement of the compatibility between satellite IoT protocols and terrestrial ones[6].

Several commercial solutions can be already found to solve a similar problem to the one that this Thesis is proposing using both GEO and LEO satellites. Some companies such as INMARSAT provide a M2M service with a network of GEO satellites with up to 1 min of latency[2], whereas many other companies have also already launched products into the market providing telemetry and M2M communications within a LEO satellite network, such as the United Arab Emirates company THURAYA[3]. A well-known satellite company as it is IRIDIUM, has its own satellite M2M service, called Short Burst Data (SBD)[4]. With this type of service, and making use of the global coverage provided by 66 satellites (divided in 6 orbital planes, with 11 satellites in each one), IRIDIUM is capable of providing a reliable connection between the host tracker and the tracked element, very useful for tracking or M2M applications such as SCADA. Both of these companies have implemented wireless devices that transmit short packages of data in a non-fixed time intervals that travel along a satellite network provided by the company itself, giving full availability for applications such as telemetry, monitoring, tracking, and many more.

[2] https://www.inmarsat.com/service-group/m2m/
[3] https://www.thuraya.com/services/ip-m2m
[4] http://www.networkinv.com/technology/m2m-telemetry-scada/iridium-short-burst-data/

This Thesis has focused the attention on small solutions (nanosatellites) whose characteristics and requirements are different from the big commercial solutions. Energy efficiency, reduced constellations or constraints on the link budget and inter-satellite links are some differences that shall be considered. There are still some papers and research yet to mention about these matters, all of them concerned on the energy efficiency of a particular satellite related to the whole cluster network acting in that scenario. All these studies center their attention in the optimization of the energy harvesting of the satellite in terms of being more efficient both in energy and spectrum in every transmission that the satellite executes[7].

Chapter 2

Methodology

The main goal of this project is, as in the previous chapter has been introduced, to simulate and evaluate different satellite scenarios taking into account the main parameters that define all the final results and measure the performance of the project, called the Key Performance Indicators (KPI). The study of the KPI is crucial in the development of this project, and this particular chapter is focused on the context and the calculation of them. Although these different scenarios will be explained in more detail in chapter 3, the concepts described in the following sections are the turning point of the whole project and the background of all the necessary calculations used for them.

2.1 Orbit Simulator

As this is a satellite-based network project, the first step is to implement an orbit simulator in order to plot the orbits of the different satellites in all the scenarios in chapter 3. To do so, a MATLAB function has been used in order to implement all kind of satellite orbits, to be later applied when calculating the KPI in each particular scenario. This function allows the user to create a vector of the latitude and the longitude of a certain satellite, by introducing the six main aspects necessary to define an orbit[8].

- **Perigee Radius in km**
- **Apogee Radius in km**
- **True anomaly at the departure in degrees [0-360]**
- **Right Ascension of the Ascending Node in degrees [0-360]**
- **Inclination in degrees [-90, 90]**
- **Argument of perigee in degrees [0-360]**

Apart from these six basic orbital elements based on the Keplerian laws, the function allows the user to define two simulation-based parameters:

- **Number of orbital periods**
- **Number of samples per orbital period**

These two final parameters are the ones that define both the length of the latitude and longitude vectors and also the time difference that each vector position has with respect to the previous one. In this project, these two values have been equally defined in all the orbits, using a simulation of 20 orbital periods with 200 number of samples per period, resulting in a column vector of 4002 elements and a time difference between them of 30 seconds. This interval time between the vector elements will be extremely important for the KPI calculation in chapter 3, as it is a significant value to take into account mostly for computing the delay.

Any orbit can be easily described with this function , e.g the orbit of an IRIDIUM satellite (86.4 degrees of inclination) with an altitude of 780 km such as the one in the figure below.

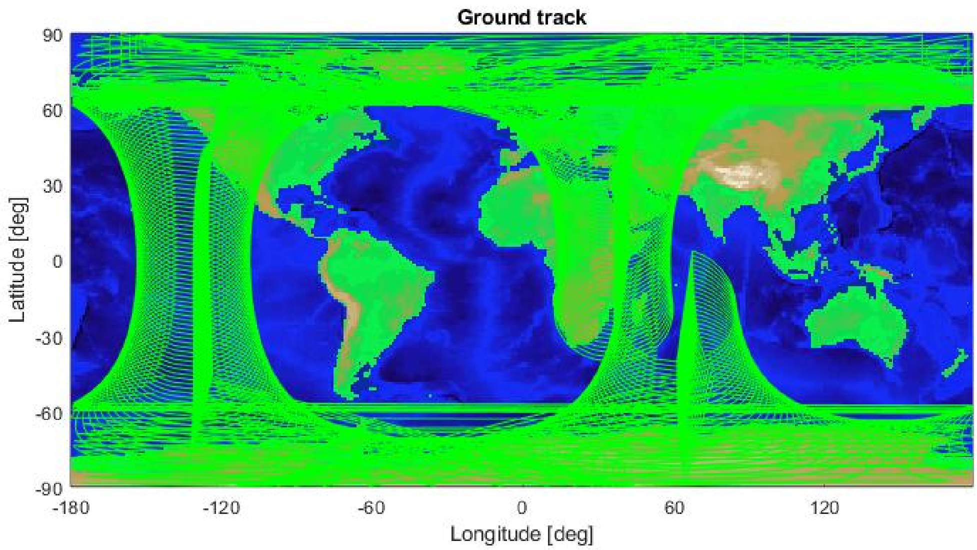

Figure 2.1: Simulation of an orbital period of an IRIDIUM satellite.

Apart from obtaining these two mentioned vectors, the function also returns the three Earth-centered inertial (ECI) coordinates (x,y and z) of the satellite in question, with the same time difference between the elements as the latitude and longitude vectors. These coordinates have the origin at the center of mass of the Earth, and will be used as well in chapter 3 to calculate the distance between two given satellites by using the following basic equation:

$$Distance_{ISL} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{2.1}$$

Eventually, this distance will be used to determine the propagation time of a signal in the case of an inter-satellite link and will be added to the total final delay time as it is a substantial value to consider.

2.2 Signal and Traffic Models

As it has been stated in the Project Statement in the previous Chapter, telemetry (in fact, all M2M applications) makes use of small packet transmissions in which all the data is compressed. These links usually work on a low-rate network sporadically sending and receiving short packets in both ends.

In satellite links, one distinction appears when clarifying the application of the satellite network, and that is the difference between the Return link and the Forward Link. The Forward link is the connection between a central station and a user terminal (e.g in satellite TV broadcasting) whereas the Return link implies a connection between a user terminal a ground station (e.g in telemetry links, such as this one)[9]. The traffic and signal model used in satellite scenarios when working with the Return Link is the second version of the Digital Video Broadcasting - Return Channel Satellite 2013 standard (DVB-RCS2). In this standard, there are multiple cases that are studied and can actually make use of this model. In this project, all the information regarding the Traffic has been extracted from the following table obtained in the official DVB-RCS2 documentation[1]. For simplicity, it has been decided that the telemetry packet sent from one end to the other in all the simulations has a size of 536 symbols, representing the Short Burst standard in the DVB-RCS2.

Table 10.9: Linear Modulation Waveforms Efficiency in AWGN Channel

Waveform ID (Table A-1 of [i.1])	Burst Size (symbols)	Guard (symbols)	Payload (bits)	Efficiency (Bits/Symbol)	Es/No @ PER=10^{-5}
44	266	4	408	1.51	7.3
45	266	4	440	1.63	8.71
46	266	4	496	1.84	10.04
47	266	4	552	2.04	11.59
48	266	4	672	2.49	11.73
49	266	4	744	2.76	13.18
3	536	4	304	0.56	0.22
4	536	4	472	0.87	2.34
5	536	4	680	1.26	4.29
6	536	4	768	1.42	5.36
7	536	4	864	1.60	6.68
8	536	4	920	1.70	8.08
9	536	4	1040	1.93	9.31
10	536	4	1152	2.13	10.85
11	536	4	1400	2.59	11.17
12	536	4	1552	2.87	12.56

Figure 2.2: DVB-RCS2 2013 Standard for Short and Very Short Burst

As it can be seen in the Figure, depending on a certain Energy per symbol to noise power spectral density (Es/N0) a different efficiency (bits/symbol) is given, and therefore, the packet can be sent with more or less bits. The efficiency value in the table contains the bits/symbol ratio of the modulation used for a certain Es/N0 and also the code used for that simulation in order to indicate the ratio of useful bits to total bits (e.g 4-QAM 4/5

[1] http://www.dvb.org/resources/public/standards/a162-DVB-RCS2-Lower-Layer-Imp-Guide.pdf

modulation with ID=7 in the table). This computation is the key to find the bit rate of the link, by following this basic equation in the satellite communications field:

$$Rb = \frac{BW}{1+\alpha} * eff \tag{2.2}$$

-where the roll-off factor is represented with the alpha symbol and represents the shape of the raised-cosine. In this project the roll-off of the signal transmission has a value of 0.35, as it is one of the most standard values that most applications use[9].

All these calculations are part of the Adaptive Coding Modulation (ACM) process that is going to be explained in the next section in order to find the bit rate of the link in a certain time to eventually calculate the latency of the signal.

2.3 Key Performance Indicators analysis

In every project there are some particular parameters that must be studied and analysed in order to see the performance of the simulation based on them. In this Thesis, these parameters are, as it has been previously introduced in this document, the delay and the energy of the satellites, translated into the inter satellite links. Both of them are equally essential to the understanding and analysis of the scenario's performance.

2.3.1 Time Delay

The first KPI to study is the time delay of the signal in an end-to-end scenario between a remote area and a monitoring station. Although the different scenarios that will be presented in Chapter 3 imply distinct delay calculations due to the differences in the satellite network, the essence of this computation has always the same skeleton.

In a satellite link, just as in a terrestrial one, there are 2 main parts, the uplink (Earth-Satellite) and the downlink (Satellite-Earth). These two links are very different from each other and the Carrier-to-Noise (C/N) can be very different depending on the application that the satellite is being used for. In this particular case -a low-rate wireless satellite network- where a small terminal communicates with the central station, the uplink C/N is much lower than the downlink (resulting in a much lower delay time in the dowlink than the uplink), as the transmission parameters of the telemetry terminal are very limited in terms of power transmitted and antenna gain[1]. To compute the C/N of the link, a typical equation in the satellite communication field is used:

$$(\frac{C}{N})_{dB} = EIRP_{dB} - (L_{fs})_{dB} - k_{dB} + (\frac{G_R}{T})_{dB} - BW_{dB} \tag{2.3}$$

-where 'EIRP' is the Effective isotropic radiated power, 'Lfs' are the free space losses, 'k' is the Boltzmann constant, 'G/T' is the ratio between the receiver gain and temperature and 'BW' is the bandwidth.

The uplink and downlink time delays are one of the main parts of the skeleton previously mentioned. Both of them consist in two time calculations, one depending on the distance and the other one on the bit rate. The first one is rather easy to measure, as the only thing that is needed is the distance between the satellite and the terminal or ground station and the satellite at a certain moment. In terms of the project simulator, the distance can be easily calculated following some trigonometrical equations, knowing the coordinates of the transmitter (remote place), the receiver (monitoring station) and the coordinates of the satellite at that given time obtained from the 4002 element vector described in the previous section. Once this distance is known, and taking into account that the light speed ('c') is 300.000 km/s, with a simple fraction it is easy to obtain the propagation time.

$$t_{dist} = \frac{distance}{c} \tag{2.4}$$

The second time is much more important to consider, as it is the time that it takes to transmit the packet depending on the bit rate. In order to compute this time, the best link conditions in the channel are assumed. To this purpose, the use of the Adaptive Coding Modulation (ACM) is the key to find the adequate bit rate in the link. However, to implement an ideal ACM scheme such as the one used in this project, the link state is necessary to be known and therefore the results obtained in the next Chapter represent the best case possible. With the ACM, the idea is to obtain a different C/N in every time step of the simulation (every 30 seconds), that immediately translates into a different Es/N0, and eventually into a different bit rate. The way to compute the Energy per symbol to noise power spectral density is the following:

$$\frac{E_s}{N_0} = \frac{C}{N} * \frac{BW}{f_s} \tag{2.5}$$

Once this value is computed, the only remaining thing is to look at the DVB-RCS2 table standard presented in the Traffic Model section, and relate the value of the Es/N0 to the according efficiency that it requires and the useful payload bits of the packet. Knowing the length of the established telemetry packet, and the bit rate at a certain time depending on the ACM, a simple fraction is required again in order to obtain the final value of this second main time delay:

$$t_{Rb} = \frac{bits_{Tx}}{Rb_{ACM}} \tag{2.6}$$

As the payload bits obtained in one packet are really small compared to the bit rate obtained in most of the scenarios, this time is usually lower than the propagation time due to the distance, specially in GEO satellite networks such as the second proposed scenario of this project.

2.3.2 The impact of ISL on Time Delay and Energy Consumption

Apart from the uplink and the downlink, there exists one more optional link that is not always present in all satellite communications but has enormous potential applications: the inter-satellite link. Although this concept has been already introduced in this document, what it actually implies to the whole communication link in terms of energy and delay has not been specified yet.

The ISL are most times the key to an end-to-end link as they "play an important role in relaying data from one satellite to another directly without the need of a ground station on Earth"[10]. Using an ISL may be very useful for the link, as it helps in creating a more quicker signal travel. As it was introduced in chapter 1, the company IRIDIUM uses 66 LEO satellites to provide global coverage in mobile and IoT applications, and the ISL between them are the main basis for it. This satellite constellation has been used in this project as the main environment to simulate the telemetry link in the scenarios including LEO satellites, but much more details are going to be explained about this system in chapter 3.

These satellite networks could not be able to work properly without the ISL during the transmission, as they help to create a continuous connectivity without having to wait any longer than the times described in the previous subsection. These times are in fact a lot minor as the distance of the satellite is usually very short and the C/N in the link is much better than a terrestrial-satellite one such as the uplink or downlink[11]. That is due to the fact that IRIDIUM uses a frequency for the ISL of 22GHz (K-Band) and the satellite transmitting and receiving parameters are more enhanced than the other two links, resulting in a nearly ideal link[12].

The routing algorithms are one of the keys to work with the ISL in these type of networks, as they help to optimize the path of the signal in all of the 66 satellites without loosing time making unnecessary satellite links. A particular routing algorithm has been proposed in this Thesis and will be introduced in chapter 3 as well, when presenting the LEO satellite network.

The important point in this section is to realise that, although making ISL is clearly the best way to create a continuous network where the delay is minimized thanks to the routing algorithms, each satellite link made is a relevant consumption of energy to take into account. A company the size of IRIDIUM obviously does not focus on saving energy in the transmissions and is only concerned on giving its users a full coverage with continuous transmission and minimum delay. There may be other companies or entities that can not compete with the economical status of IRIDIUM, but that want to provide a similar service with a much lower cost, both in economical and engineering terms. In these cases, time delay is not the primary issue of the link, but the energy saving and satellite fabrication are, so a case where the least amount of ISL must be done without a major concern on the time delay may occur. It is in this type of scenarios where the nanosatellites turn into the heart of the matter.

Nanosatellites are, as the name states, satellites with usually very small dimensions with respect to regular ones, with the advantages that they are rather easy and cheap to fabricate and maintain[2]. They obviously have worst link budget parameters than IRIDIUM satellites (worst antenna gain, worst power transmitted, and so on) but they may be very useful in

[2] https://spectrum.ieee.org/tech-talk/aerospace/robotic-exploration/autonomous-nanosatellites-satellites-that-make-up-their-mind

terms of saving energy if the delay in the particular application they are being used is not crucial. In the next two figures below, a substantial change in the link budget parameters can be seen.

SL.NO	Parameters	Symbols	Values	Result	Units (in dB)
1	Transmitting power	Pt	10		dBW
2	Transmitting gain	Gt	3		dBW
3	Equivalent isotropic radiated power	EIRP		30	dBW
4	Bandwidth	BW	70.79		dBHz
5	Temperature	T	24.624		dBk
6	Boltzmann's constant	K	228.6		dBW/k/hz
7	Received gain	Gr	3		dB
8	Frequency	F	184.34		dB
9	Free space loss	FSL	154.63		dB
10	Atmospheric loss	La	1		dB
11	Polarization loss	Lp	3		dB
12	Antennae misalignment loss	Lant	1		dB
13	Received power	Pr		-123.63	dBW
14	(G/T)ratio	G/T	-21.624		dB
15	(C/N)up	(C/N)		7.35	dB

Figure 2.3: Link Budget parameters of an IRIDIUM satellite

Transmitter power	0.5 W
Transmitter power	27 dBm
TTC antenna gain	-6 dBi
Transmission Losses	0.1 dB
Tx Impedance mismatch	0.5 dB
EIRP	$27 - 6 - 0.1 - 0.5 = 20.4dBm$
Distance (H=800 Km, $\alpha = 15^o$, f=437 MHz)	2030 Km
Free-space basic transmission loss	151.4 dB
Atmospheric loss	0.18 dB
Polarization loss	3 dBi
Basic transmission loss	154.58 dB

Figure 2.4: Link Budget parameters of a HUMSAT-D nanosatellite

All these parameters have been used as the main aspects of the physical layer of the link for the multiple scenarios in chapter 3 in order to obtain the final simulations. Although the constant parameters such as the power transmitted, the antenna gains and polarization losses have been used with the same value as the ones from the tables for the simulations, some other ones have been adapted to the consequent telemetry application that this project is working on (e.g frequency and bandwidth values).

As for the uplink, where some transmission parameters such as the ones from the satellites in the figures above are needed as well, a real telemetry instrument sold by the Electronics for Imaging (EFI) company has been used as an inspiration for these link budget specifications[3].

2.3.3 Final Time Delay Computation

All three times explained in this chapter included in the total transmission time computing encounter themselves in the milliseconds range, and optimizing the system in order to shorten them is crucial in continuous link scenarios (full coverage). In the other scenarios where the transmission is not continuous (the partial coverage scenario in chapter 3), most of the times the signal has to wait stored in one satellite in order to be transmitted whenever there is an available and continuous link. That is when the need for a routing algorithm appears and is totally relevant for the delay calculation. Although this routing is meant to be explained in the next chapter, it is important to know this 'storing time' when computing the final delay time.

In terms of this project's simulator, this 'storing time' is the time difference in the longitude and latitude vector already explained (30 seconds approx.) that must be waited. Once this 30 seconds have passed, all satellites are shifted and the whole constellation has changed. If within these 30 seconds the link can not be properly established, another time step in the simulation passes and 30 more seconds are added to the storing time value. This is an iteration process that concludes whenever the transmission has been completed, but some minutes (even hours) may have passed depending on how much a satellite has stored the packet. This time can be extracted from the position in the latitude and longitude vector of that given satellite. The final computation of the delay signal would be the following, if we assume the two delay times explained above for the uplink, downlink and the ISL, with the additional storing time:

$$t_{delay} = (t_{UP})_{dist} + (t_{DOWN})_{dist} + (t_{ISL})_{dist} + (t_{UP})_{Rb} + (t_{DOWN})_{Rb} + (t_{ISL})_{Rb} + k * dt \quad (2.7)$$

- where k=[0,1,2,3...] is a positive integer representing the number of times that the 'dt' (time difference) has passed. In cases where the transmission is continuous the integer 'k' value is 0 as there is no need for a waiting time. However, this 'dt' gains more importance in the cases where the transmission is not continuous as the other six times in the equation are almost negligible due to their milliseconds value.

[3] http://www.efitechnology.com/telemetry.html

Chapter 3

Implementation

To create multiple practical and realistic cases of a low-rate satellite network, four main scenarios have been defined in order to emulate them to see how would they perform in this type of application. As it has been explained in both of the previous Chapters, a telemetry link between a remote place and a monitoring station widely separated is established. Anchorage (62,2ºN, 149ºW) and Barcelona (40,1ºN, 2ºE) are the remote place and monitoring station (respectively) chosen for all the following scenarios. Note that the two ends of this link are completely arbitrary, and they have been chosen purely for distance and free will reasons. It is specially important to comment that the specific results of the KPI (delay and number of ISL) obtained in the following sections depend on this decision but not the general conclusions obtained in all the following Figures, specially in the last scenario.

All the concepts from the previous Chapter are used both in the simulation of the scenarios and the calculation of the KPI for each one. These scenarios differ a lot from themselves, not only in the type of the orbit (GEO or LEO) but also in the number of satellites applied (1,3,N....66) and the type of the satellite (regular size or nanosatellite). The main objective of this Chapter is to define these scenarios and obtain multiple tables and figures to later on compare them and evaluate them.

It is very important to take into account that these scenarios have a thing in common, which is that a transmission of only one telemetry packet is simulated. This packet has the length of the DVB-RCS2 Short Burst, 536 symbols, due to the exposed reasons in Chapter 2.

3.1 1 Low-Earth Orbit Satellite

The first scenario for this project is a rather simple one, in which a single LEO satellite is used to create a singe-based satellite network to provide the communication between Anchorange and Barcelona. In this particular case, there exist no inter-satellite links and only the uplink and downlink times will apply in the total latency computation. The IRIDIUM satellite constellation is one of the keys to this project, specially in the third section of this Chapter. In order to get to know the performance of one single satellite before studying the whole constellation, the chosen LEO in this scenario replicates the orbital position of one IRIDIUM satellite, containing the following main orbit parameters:

- **Type of Orbit: Polar**
- **Orbital Period: 98 min**
- **Height: 780km**
- **Orbit Inclination: 86.4º**

A representation of the coverage of the LEO satellite over Anchorage (green) and Barcelona (magenta) can be seen in the following Figure:

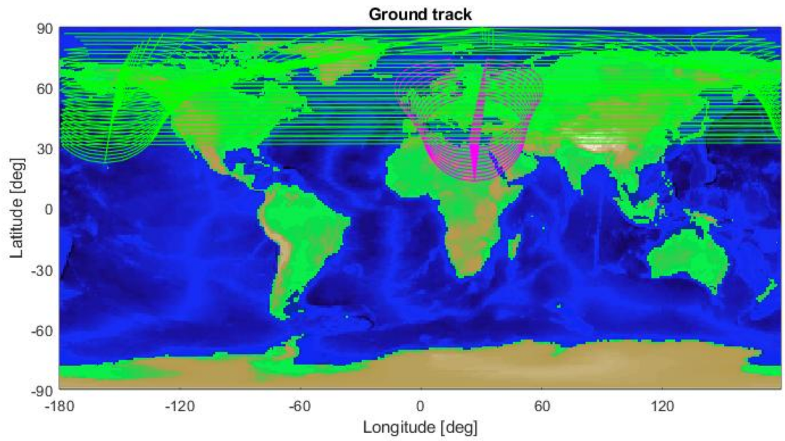

Figure 3.1: Coverage of both ends of the link by the LEO satellite

The simulation results of this first basic unrealistic scenario show that, as there is no direct link between Anchorange and Barcelona, the latency is about 77 minutes. As it has been explained in the previous chapter, in this case the uplink and downlink times are negligible in front of the storage time when the satellite keeps the packet. Note that this is a result that depends on the distance between the two ends of the link and the orbit of the LEO satellite, and a change in one or both of these parameters could cause an increase or decrease in this value. There may be other satellite orbits that could optimize the delay in a few minutes, but the long distance between them would imply nevertheless a huge delay in the link.

As this is only the first scenario of this project and its performance is just introductory for the following ones, this scenario has not been tried to be optimized rather than be presented as the worst case scenario. However, these 77 minutes are the result of the simulation at a certain time, and due to the rotation of the Earth and the shift of the orbit, it may happen that the delay between Anchorage and Barcelona is larger or lower than 77 minutes. For that reason, an iteration over the existing iteration is done in order to compute the mean value of the signal's delay. This is done by running the simulation every 5 minutes (or every 10 vector elements, which is the same) and saving the result of the time in a vector to later on compute an average function to it. This procedure applies for all the following sections as well, specially in the last two scenarios including LEO constellations.

Due to the order of magnitude of this time delay, it is almost impossible to consider it for a real scenario where only one satellite would be applied for this type of communication. In addition to this, there exists another possible problem. In this scenario, it has been shown that from the orbital position of the satellite it only covers both spots for about 10 minutes, so if a much bigger message should be sent (not just a single packet) or many other devices wanted to transmit from Anchorage, and if these 10 minutes weren't enough for the satellite to obtain all these information, a whole period orbit would have to be waited in order to continue the data transmission.

Knowing all this information, it is clear that a full coverage of the Earth should be implemented, and it can be done by using a network of both GEO satellites and LEO satellites.

3.2 Global Coverage by 3 Geosynchronous Satellites

The second proposed scenario is a more realistic one but rather inefficient, as the results will show. It is based on a satellite system of three GEO satellites, located equally in the Earth equator with a separation of 120°, resulting in a full global coverage of the Earth, except the North and South poles. Unlike the previous scenario, this type of network creates a continuous link between two widely separated spots such as Anchorage and Barcelona, but has still some problems attached.

First of all, GEO satellites are often used for applications such as weather and Earth Observation and TV broadcasting, therefore they are not suited for scenarios that imply inter-satellite link due to their huge distance (a GEO satellite has a height of 35786km) between them and the ground stations. These huge distances create a lot of attenuation in the link and require to enhance a lot other parameters to compensate these free space losses. LEO satellites are more suited for the ISL scenarios as they present less latency and their position is not 'fixed' from the Earth point of view, differentiating themselves from the GEO satellites, that move at the same angular velocity as the Earth and appear to be in the same spot always when looking at them from the Earth[13]. Nevertheless, in this scenario an ISL between the GEO satellites is considered in order to evaluate the propagation delay with the global coverage that provides this network.

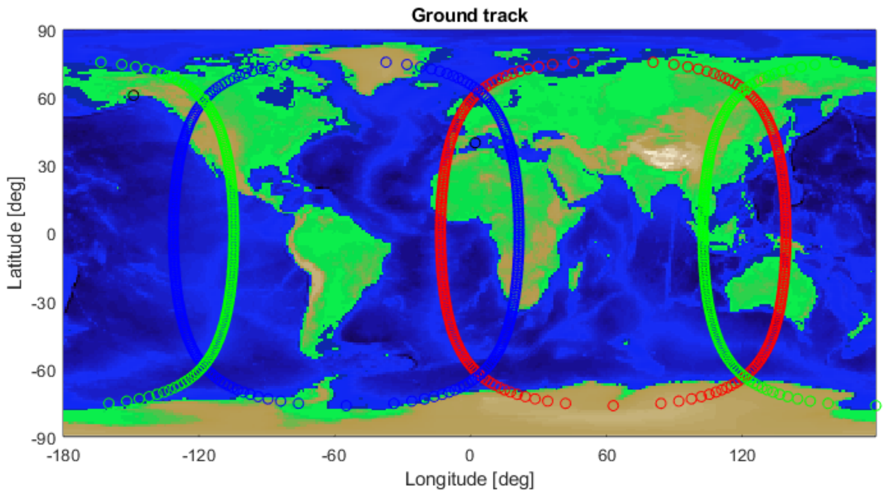

Figure 3.2: Coverage of the Earth by 3 GEO satellites with an Elevation of 5°

As it can be seen in the figure above obtained from the Orbit Simulator, one single GEO satellite cannot connect Anchorage with Barcelona (marked with a black marker), so an ISL between the GEO with the green coverage and the GEO with the blue coverage is needed. As they are fixed and their position does not change in time, these GEO satellites could have not been simulated with a vector using the orbit MATLAB function, but in order to obtain more accuracy in the latency computation, is has been done just as the LEO satellites. The result is also a 4002 elements vector simulating a total of 20 period orbits, but is much more exact as the latitude and longitude change a bit in the past of time, which is what happens in reality. Regarding the physical layer of the link, the ISL between GEO satellites has been simulated with a frequency of 60GHz, as some of the recent studies in this field explained in the State of the Art are stating in the past few years.

Following all the calculations explained in Chapter 2, and unlike the previous case, the times related to the distance and the ACM are much more significant, specially the distance one between the two GEO satellites that share the data in the ISL. The uplink and downlink times are about 120ms due to the distance (same as the standard GEO communications), but the ISL time is about 240ms. The ISL distance is obtained making use of the trigonometrical equation and ECI coordinates explained in the previous chapter, and a distance of 72.000km between two consecutive GEO satellites is the result of it. This huge distance causes a delay in the communications of almost a quarter of a second. As the packet is very short, the time regarding its transmission is much minor than the distance one and only adds about 10 ms to the total latency time, which has a value of more than half a second, 538ms concretely.

Seeing this result, it is obvious that an L-Band application such as mobile communication is difficult to be implemented with a GEO satellites network. However, as it has been previously said, the telemetry and M2M applications also work in this frequency band, and this kind of delay may not be a problem, depending on the case. Some applications like monitoring of industry assets (which is one telemetry use) don't really need short latency communications and this type of network would suit in what time concerns. This time would increase more when regarding the multiple access and protocol network techniques, but still would be adequate for certain telemetry applications that don't require low latency transmissions.

3.3 Global Coverage by Low-Earth Orbit Satellites

The third proposed scenario in this project is a network full of LEO satellites providing global coverage. This section is dedicated to the definition of the scenario and the evaluation of its KPI. As it has been previously stated, the IRIDIUM satellite constellation has been the inspiration for this scenario. In Chapter 1 this network has been briefly explained, but there are more key details that need to be explained, as they are imperative for the routing algorithm.

The IRIDIUM satellite network is based on 66 LEO satellites divided in 6 orbital planes (all of them with the characteristics that the orbit in the first scenario have) with 11 satellites equally distributed in each one, resulting in a separation of 32.72° between them. In order to not collide both in the North and the South Poles, all the orbits are shifted from the contiguous one in 16.4°, which is precisely the half of the separation between the 11 satellites in one concrete orbit. A more visual portrayal of this constellation can be seen in the next figure[1].

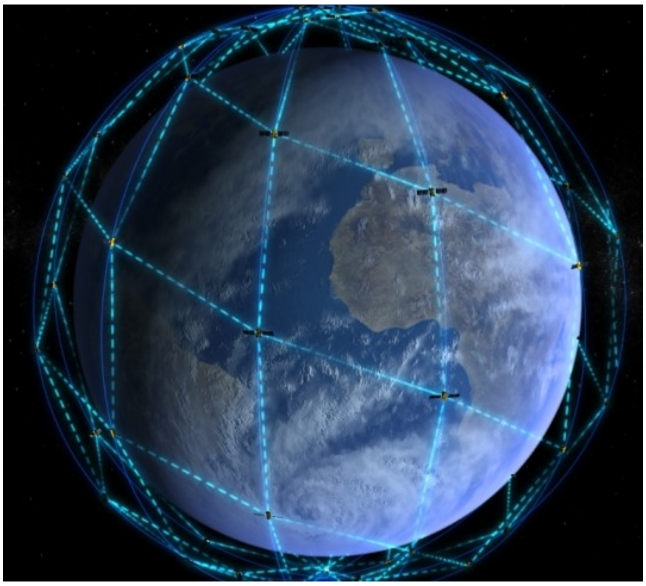

Figure 3.3: 3D representation of the IRIDIUM satellite network

Apart from the constellation itself, it is very important to remark one thing regarding the connection between satellites. As it can be seen in the figure, not all satellites connect to each other. Every satellite has a total of 4 inter-satellite available links: 2 links with the satellites in front and behind in the same orbital plane, and 1 link with the contiguous orbits on each side. These ISL are, as it has been mentioned in Chapter 2, almost ideal, as the link frequency is very high resulting in a bit rate of 10Mbps. Therefore, in the total calculation of the latency for this scenario, the time needed to transmit the packet is much lower than the propagation delay, specially when the satellites are near the equator because the gap between them is larger than when they are near the Poles.

[1]https://www.thalesgroup.com/en/worldwide/space/press-release/iridiumr-next-constellation-built-thales-alenia-space-now-completely

3.3.1 ISL Routing Algorithm and Latency Analysis

All 66 satellites have been simulated with the Orbit Simulator, and a 66-row matrix full of 4002 element vectors containing the latitude and longitude values is created. Another matrix containing the C/N values of the uplink and the downlink is created in order to see which satellite has better visibility of Barcelona or Anchorage at a certain time. These matrices are extremely helpful when computing the KPI following the routing algorithm and are the first step before computing the final time delay. This algorithm is directly related to the number of inter-satellite links that want to be used for the connection between Anchorange and Barcelona.

The algorithm consists on creating 'boxes' between the starting satellite that receives the telemetry packet and the satellite that is going to send it finally to the ground station. These two satellites are selected from the rows of the uplink and downlink matrices that have the highest C/N. When the row is obtained, it is easy to obtain the latitude and longitude vector of those satellites, as they are in the same row in the latitude and longitude matrix. Once the 'receiver' satellite and the 'sender' satellite are known, following the figure of the IRIDIUM satellite network a 'box' is created between them, as it is obvious that the optimal path of the signal is inside it. To set an example of it, here is a figure representing a satellite 'A' that wants to inter-connect with a satellite 'F' within the IRIDIUM network.

Figure 3.4: Example of the routing algorithm for a non-defined number of ISL

In this particular case, within the box appear four more satellites, and a lot of paths can be obtained from that. Earlier in this Chapter it has been said that the distance between satellites is much minor when near the Poles rather than the Earth equator, and this is precisely the way to find the optimal path. In this case, the satellite would transmit the signal to satellite 'F' through satellites 'D' and 'E' (a total of 3 ISL), as they are closer to the South Pole and the distance between them is smaller than all the other paths. Although there are multiple three ISL paths in this box, the one containing the mentioned satellites is the optimal one with the lowest delay. This type of solution applies for every routing case (both in the North and South Poles) but does not depend on the number of inter-satellite links. In other words, in this case there is no imposition on how many ISL the signal must have, and the routing algorithm simply finds the optimal path where the delay is minimal.

As the distance between the satellites and the ground stations and with the contiguous satellites is lower than in the previous GEO satellites case, the times are much smaller. It is important to take into account as well that, as the case of the global coverage creates an immediate transmission, packets are no necessary to be stored in the satellite and can be immediately transmitted. The final result is that around 50ms are needed to transmit the packet from Anchorage to Barcelona, after applying the routing algorithm and having created the mentioned 'box' between the receiver and sender satellites. In this particular case, 4 ISL are needed in order to connect both ends of the link. As the routing box is created near the North Pole, the signal travels through the optimal path with four inter-satellite links in the upper side of the box, where the distance is smaller.

Another important point is to observe that if the simulation of the orbit starts at a different time from the initial one, it may happen that the optimal path between Anchorage and Barcelona only requires 3 inter-satellite links. Following this assumption and the explanation made in the first scenario, the mean value should be computed for both the delay of the signal and the number of 'hops' (ISL) between satellite that it does. The results show that the mean number of ISL for this link is 3.82 and that the mean minimum delay decreases up to 45ms. These are in fact a much more realistic values than the ones before.

The routing algorithm gets another approach when a defined number of ISL is wanted for the transmission. In a case that there where a constraint on the number of ISL, the less ISL the more delay it would get the link. The constraint to a certain number of ISL, lower than the optimal one, would be due to the possibility of saving a lot of energy that a satellite wastes every time a transmission such as an ISL is done as well as reducing the potential network congestion. The approach of this project to do this, is that the satellite that first receives the packet is the one that will keep it until the box between it and the receiver satellite contains a path with the defined number of ISL. In other words, the receiver satellite is fixed and the sender is variable. At the beginning of every simulation, the first satellite that passes through Anchorage is the one that keeps the packet and orbits until it reaches a point where with only one, two or three ISL can reach the sender satellite. This means that, in every iteration, a box between the receiver satellite and the satellite with the major C/N in Barcelona is made, and if it fits with the requirements of the number of ISL imposed, the link will be available or not. If it is not convenient, the simulation advances until the link can be done. This leads to a rather interesting figure that compares in fact the delay in the transmission with a finite number of ISL in the LEO network.

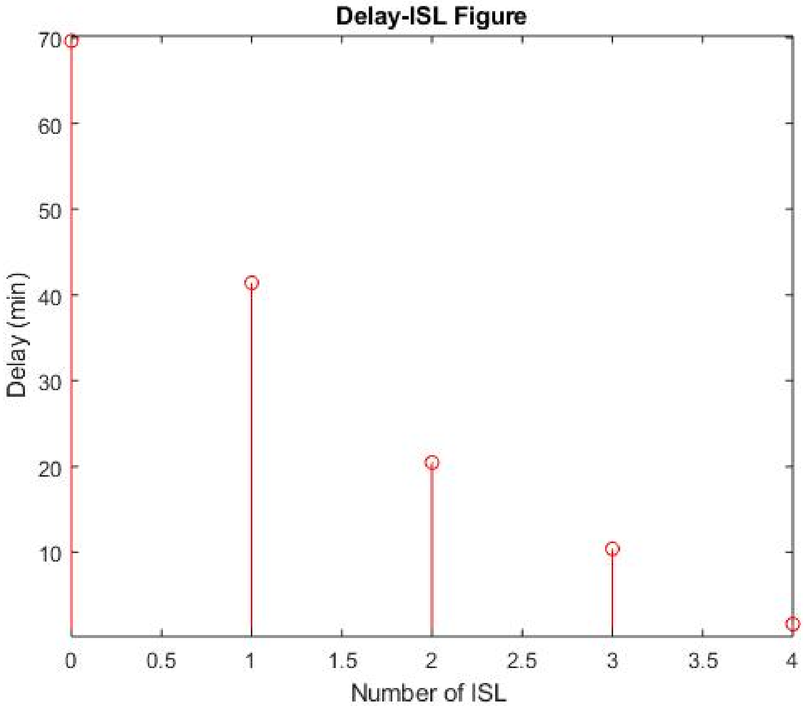

Figure 3.5: Relation between the delay in minutes and the number of inter-satellite links in the transmission

In the figure above it can be easily seen the exponential decrease of the delay in front of the number of ISL. The left side of the plot (0 ISL) represents a case in which no inter-satellite link is requested for the transmission and therefore it is basically the same delay as the first proposed scenario in this Chapter, where only one LEO satellite was available. At the opposite side (4 ISL) the delay time is almost a minute as, although most of the times the optimal number of ISL is 4 (the mean value is 3.82) and the minimum delay is given, there are some moments in the simulation where 5 ISL are required in order to transmit instantaneously. When this case is given, fixing 4 ISL to make the link available makes the simulation not to be completed immediately as the satellite has to keep the packet some time. Between these two sides, the delay decreases exponentially as expected, and with every ISL made, there is a gain between 15 and 20 minutes in the latency.

However, in a real case scenario, and as stated in Chapter 2, the idea of a company like IRIDIUM fixing ISL and obtaining a lot of delay such as the figure suggests is totally fictitious. Small satellites (e.g Nanosatellites) make a lot more sense in this type of cases and, following all the physical layer parameters explained in the previous chapter, this project seeks to find a way to optimize the small satellite network in terms of energy, delay and economical costs.

3.4 Partial Global Coverage by Low-Earth Orbit Satellites

The fourth and last scenario of this Chapter is entirely related to the previous one, as it continues to be a LEO satellite network with the same ISL algorithm, except from the fact that the big sized satellites have been changed by nanosatellites. As their coverage area is smaller than a big satellite, the height of the orbit has been changed to 600km, which is where they typically orbit on[14]. This difference in the altitude changes the orbital period from 98 min to 96 min and a slight change in the delay computation which is going to be explained later in this section. The rest of the orbit parameters have been left the same as the other ones.

In this particular scenario the approach is different than in the full coverage case. Time delay is an important issue in the link and should always be prioritized, but when working with nanosatellites things are different. Using nanosatellites implies that big satellites can not be afforded and saving energy becomes the key in the network. Therefore, the procedure to do so is not only focused on how many inter-satellite links exist in the studied connection between Anchorange and Barcelona, but also in how many nanosatellites are in the network.

Decreasing the number of the satellites in the network has an advantage and a disadvantage. On the one hand, less satellites in the constellation would obviously create an increase on the latency, as the network does not provide global coverage of the Earth, only a partial one. On the other hand, although this is clearly a drawback, this would definitely imply a lot of saving in both economical and energy terms, as less satellites implies less inter-satellite links and a lot cheaper cost when manufacturing nanosatellites (the average cost of a nanosatellite is 100.000 dollars[2]).

This project has followed this idea with the 66 satellite IRIDIUM constellation as a starting point. To observe the increasing delay time in front of the number of satellites, a simulation has been done by using a number of satellites multiple of 6 (from 1 to 66). In each case, the routing algorithm is the first presented one, focused on finding the better path of the signal to obtain the lowest time delay. The routing adapts itself to the given constellation but acts the same way in every case.

The six orbital planes of the constellation do not change throughout the multiple scenarios, but the number of satellites in them does, and consequently the separation in degrees between them changes. For example, in the 60 satellites case, there are 6 orbital planes containing 10 satellites in each one, resulting in a separation between them of 36°, a bit bigger than the 66 satellite case, where the gap was 32.7°. The difference in the angle follows the simple equation:

$$\triangle\,\phi = \frac{360^o}{k} \tag{3.1}$$

- where k=[1,2,...,10]. It has been said though, that the interval was [1,66], but the single satellite case is not considered in this equation, as it is the same as the first scenario presented in this Chapter, or when simulating a network with no inter-satellite links like in the previous section.

[2] https://alen.space/nanosatellite-solutions-ready-to-launch/

It is important to remark that, as the number of satellites decreases the latency increases, and the inter-satellite link time does as well due to the bigger distance that exists between satellites. However, the storing time of the satellite is a lot more significant than this time and turns out to be negligible once again. In cases where there are few satellites, there may be times where there is no satellite near Anchorage to deliver the telemetry packet and therefore the telemetry instrument must store the packet until it transmits it to a satellite covering the area. The same happens on the other end: if the receiver satellite can not deliver to the sender satellite because there is no direct connection with Barcelona, the routing algorithm applies and the receiving satellite keeps the packet until it can be properly transmitted.

Following all these specifications and with the modified parameters of both the orbits and the nanosatellites applied to the simulation, the next figure is obtained. In addition, the mean value of the delay time has been calculated, to obtain more realistic and reliable data.

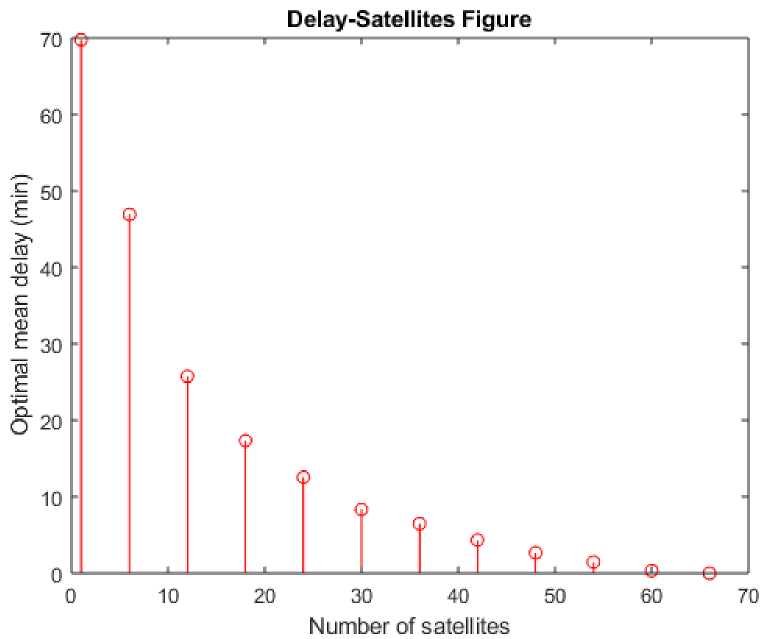

Figure 3.6: Relation between the number of satellites and the optimal mean delay in minutes

From the obtained Figure above a lot of things can be concluded. As it can be seen, the delay starts at the left side at 71 minutes, which is the mean delay of a single satellite case such as the first one in this Chapter. From this value, the latency decreases exponentially with a big decrease in the first simulations, when using only 6,12 and 18 nanosatellites. From there, the delay only decreases less and less every time 6 satellites are included to the network, until reaching the right side of the figure where the value is about 40ms. These 40 ms represent the mean value of the delay in the full coverage scenario that in the previous section was 45ms. It has decreased a bit in this last scenario as the distance between the two ends of the link and the satellite has decreased from 780km to 600km, and therefore the distance in the ISL is lower as well. This change in the altitude of the satellites makes a difference of approximately 0.6ms in both the uplink and the downlink, and about a millisecond in the ISL. All these variations in the values eventually create a deviation of 5ms in the final mean delay computation.

This Figure would imply that, if the delay is not prioritized in a M2M case such as this one, a network with 'only' 10 minutes of delay could be implemented with the half of the 66 satellites required for a global coverage of the Earth, and a lot of money could be saved from that. Even with only 12 satellites, in half an hour the telemetry packet could be received in Barcelona, and this would be ideal for cases in which the telemetry does not require a minor latency and only certain information every certain time is demanded (e.g temperature and humidity sensors).

As stated a few paragraphs above, less satellites imply more delay and less ISL. As they are directly related between them, another study has been made regarding the average number of inter-satellite links that are used in every case and the amount of satellites used. Once again, the values from the previous sections are used for both ends of the following table, considering that with 1 satellite there are no ISL and with 66 the average number of ISL is 3.82.

Number of satellites	Optimal mean ISL
6	1.91
12	2.42
18	2.80
24	3.01
30	3.15
36	3.32
42	3.45
48	3.54
54	3.63
60	3.71
66	3.82

Table 3.1: Comparison between the number of satellites in the network and the number of optimal mean ISL

As shown in the table, it is clear that the statement made earlier regarding the increase of the inter-satellite link with the increase of the number of satellites is fulfilled. However, something very interesting is noticeable as well. The table is strictly associated with the last figure, as there is a direct relation between the big decrease in the optimal mean delay and the optimal mean inter-satellite links. A big decrease in the delay appears when adding 6 satellites with up to 18, and it is precisely in this stages of the simulation in which the table shows that the ISL increases a lot. With only 6 satellites, the network needs an average of only 1.91 ISL to complete the link, whereas when having 12 this value increases up to 2.42, and it is not until 24 satellites are in the network that 3 average ISL are needed. From that point, it does not change much until the final value (3.82), just like the delay figure, that from the 24 satellites case to the full coverage case the delay only changes in 10 minutes.

Although the study of this Thesis is focused on the transmission of one packet, all the results obtained from the tables and figures in the different sections of this Chapter may be the key for a business and engineering strategic plan of a company willing to provide the service (or at least a similar one) that this project is presenting.

Chapter 4

Conclusions and further research

The main objectives of this Project were twofold: to analyse different satellite scenarios including both GEO and LEO satellites in order to study the latency that they imply and later on use these delay values to discuss the trade-off between the energy and time that appears. The results obtained in the previous Chapter lead to a series of different conclusions and open other doors for future research on this matter.

The reasons to study both the normal satellites and nanosatellites have already been explained, but not the impact that the obtained results may have. As it has been said, the most interesting part about nanosatellites is that they are easy to manufacture and they are a lot cheaper than a normal one. If the results of the last section of the previous Chapter are added to this, the potential of using nanosatellites that outcomes from it is huge. A small-size company could easily compete with big companies such as IRIDIUM just by creating a nanosatellite network made out of the half of the IRIDIUM one, and providing the same service in L-Band (except mobile services) with 'only' a 10 minutes delay. Although nanosatellites are really new and have not been used yet for this kind of application, they may be the key to the future for small entities willing to make a step forward in the satellite world. This Thesis has tried to be a small part to it by providing these simulations, even though there are a lot of issues to improve before it could be really used in a future project plan.

One of the first and most principal parts in which this project could be improved is in the routing algorithm. There are much more complex routing systems already implemented or being studied that contain algorithms based on probabilities, paths and decision trees (presented in the State of the Art), in which the signal is decided to be sent or kept by the satellite in question by calculating at every step which is the best option in order to obtain the smaller time delay. In this project a simpler solution has been given regarding this matter, as there is only one satellite that keeps the packet when it can no be immediately transmitted and keeps it until the other satellite is reachable. As the intention of this project was to study both the energy and the time and the difference in them that a given number of satellites can create, computing and programming an ideal or much more complex routing algorithm was not the main issue. Therefore, trying to improve the latency of the satellite network regarding the number of satellites and the ISL could be the first approach that a future project could try to focus on.

Another area that could be improved is the length of the sent message that is required to be transmitted between the transmitter and the receiver locations. Throughout this project it has been emphasized several times that the simulation is based only in the transmission of one telemetry packet, based on the Short Burst in the DVB-RCS2 standard. However, it could be the case that a much more larger message than just one packet wants to be forwarded (e.g a message that includes all the telemetry information of one day of all the terminals in a specific remote area) and can not be fully transmitted in the time space of only one satellite coverage. In this case, one part of the message would be sent to one satellite, and the rest of it to the next one, and the routing algorithm should apply for both of them to arrive at the same destination, where they should be unified again.

Another different point of view of this future implementation is the use of multiple access techniques. In the previous case it was considered a single large message that includes too much information to be forwarded in a single satellite coverage, but in this one it is considered that multiple terminals are willing to transmit at the same time to one satellite (e.g different temperature sensors in a remote area that transmit their telemetry packets to the same satellite covering the area). In this case, a multiple access technique should be used in order to send all packets correctly to the same satellite without interfering themselves. Time-Division Multiple Access (TDMA) or Frequency-Division Multiple Access (FDMA) are usually the most implemented methods used in satellite communications nowadays, and they are now being mixed with the latest proposed routing algorithms[15]. Including these multiple access techniques would increase the delay in most of the cases, as it would take into account all the time that is lost until all the packages are sent and received, and in some cases, these multiple access techniques would have to be implemented in more than two satellites when there is no time for one to get all the information during its coverage time.

Another restriction for this to happen would be in the cases in which the satellite is implemented with a certain memory buffer that has a maximum capacity. If all the packets transmitted at the same time were able to surpass this capacity, the system would have to wait until the next satellite covering the area in order to continue the transmission. All these waiting times would definitely create a significant increase in the final computation of the delay, but they would make the simulation a lot more realistic and reliable.

A last implementation regarding the energy of the satellites may be done. In this project it has been considered that any inter-satellite link at any time is operative, but there has not been any approach on how the satellites get their energy or consume it. All of them get their energy from the radiation of the Sun, as most of the satellites nowadays have a pair of solar cells panels in each side. These panels convert the sun light in electric power, which is later used for both the transmissions between satellites and with the ground stations. However, due to the rotation of the Earth, there is not always direct radiation from the Sun and that is why during the night, most satellites have to make use of their batteries in order to be able to work and be available without concern of the Sun.

According to some studies, "Satellites in LEO constellations can spend over 30% of their time under the earth's umbra"[16], and in that time is when the batteries discharge themselves as they are being used as the power supplying of the satellite. During this time, the "depth of discharge they reach during eclipse significantly affects their lifetime - and by extension, the service life of the satellites themselves". In this project the eclipse phenomena is not considered, and it could be applied in two ways: either considering a complex simulation taking into account all the parameters of an energy harvesting system of a satellite, or a more simple approach based on a binary solution. This last one would imply that when the satellite is in Earth's umbra is shut off because it does not have any batteries in its energy system, and it is only powered on when there is a direct impact of Sun light into the solar panels.

The binary solution would even be realistically considered in the nanosatellites case, in which it may be occur that the complex energy system can not be implemented and the nanosatellite should be shut off every time is in Earth's umbra. This approach would definitely affect the time delay as the ISL could not be always given, and the routing algorithm should also be improved and changed in order to recognize whenever the satellite has a direct or indirect contact with the Sun radiation.

All this further research could be done in order to implement a real case scenario of the M2M link that this project is based on. Although the results obtained at the end of Chapter 3 are very compelling, there are still many open fronts in which this project could be improved in a near future such as the ones presented in this Chapter. Along with a deep economical analysis, if this project were to be improved in these matters so as to obtain more realistic results, it could be used as an engineering previous study for an application similar to this one.

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